Fabrication and Testing of Gas-Filled Targets for Large-Scale Plasma Experiments on Nova

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Introduction

The proposed next-generation ICF facility, the National Ignition Facility (NIF), is designed to produce energy gain from x-ray heated "indirect-drive" fuel capsules. For indirect-drive targets, laser light heats the inside of the Au hohlraum wall and produces x rays which in turn heat and implode the capsule to produce fusion conditions in the fuel.[1] Unlike Nova targets, in NIF-scale targets laser light will propagate through several millimeters of gas, producing a plasma, before impinging upon the Au hohlraum wall. The purpose of the gas-produced plasma is to provide sufficient pressure to keep the radiating Au surface from expanding excessively into the hohlraum cavity. Excessive expansion of the Au wall interacts with the laser pulse and degrades the drive symmetry of the capsule implosion.

We have begun an experimental campaign on the Nova laser to study the effect of hohlraum gas on both laser–plasma interaction and implosion symmetry.[1,2] In our current NIF target design, the calculated plasma electron temperature is $T_e \approx 3$ keV and the electron density is $n_e \approx 10^{21}$ cm^{-3}. To simulate NIF conditions in a Nova target requires a target with a gas confined in an ~0.01 cm^3 vol. at ≈1 atm.[2] These gas-filled targets are calculated to produce the required plasma conditions based on an initial gas fill of 1 atm neopentane C_5H_{12}. To measure the T_e of the plasma by spectroscopic line ratios, Ar and Cl bearing gases are added to the mixtures. Metal coated carbon fibers and plastic foils are added as an additional spectroscopic temperature diagnostic. Changes in n_e are made by varying the density of the main and spectroscopic seed gases. To aid in diagnosing the plasma, additional features such as diagnostic shields, x-ray backlighting patches, and imaging slits are added to the target design as experimental requirements dictated.

To study these plasma conditions, targets are being fabricated and shot on the Nova laser using open- and closed-geometric designs. *Open geometry* refers to the gas-bag style targets that have a fairly unlimited or open diagnostic view of the plasma and are nearly spherical, plastic gas cells built on a metal or plastic support ring.[3,4] *Closed geometry* refers to indirect-drive style targets with a radiation enclosure that confines the plasma within a cylindrical Au hohlraum.[1,2] Views of the plasma in a closed-geometry target are through diagnostic holes or slots cut into the wall of the Au hohlraum and covered with gas-tight patches. This article describes the major steps and processes necessary to fabricate, test, and deliver these gas targets for shots on the Nova laser at LLNL.

Target Design

To fabricate these gas-filled Nova targets to simulate the NIF-like conditions, we integrate a gas manifold with a pressure transducer, the target and gas fill lines, gas mixing, testing and filling systems, and the Nova target positioner. To ensure a proper fit and interference with existing target handling hardware, we analyze scaled computer-aided design (CAD) drawings of the target and associated components.

Figure 1 is a CAD drawing of a closed-geometry target. CAD drawings are essential for the closed-geometry targets to allow the precise placement of shields, fibers, foils, and other target components relative to diagnostics on the Nova target chamber. In three dimensions, alignment tolerances for the closed-geometry targets are ±25 μm and ≤ 2°.

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Target Material Selection and Fabrication

To aid in target and feature alignment at the Nova target chamber, both types of targets need an optically transparent, thin, low-Z ductile material for the gas / vacuum barrier. The density of the gas is chosen so that when completely ionized and heated to 3 keV, the electron pressure will be sufficient to significantly slow the hohlraum wall motion in a NIF target. The density cannot be too large, however, or the plasma n_e will exceed the critical value for 0.25 µm light propagation, resulting in complete reflection of the incident light. The density of 3 mg / cm^3 of neopentane results in a 0.1 critical density (10^{21} electrons / cm^3), which is calculated to hold off wall motion and to allow light propagation to the wall for x-ray conversion. Ideally, actual NIF hohlraums, or experiments to simulate NIF hohlraum conditions for testing the laser–plasma interaction physics, would have no solid-material gas barriers. Early in a laser shot, these barriers, or windows, are heated to a plasma state and rapidly expand, severely perturbing the interior gas. The windows must be as thin as possible to reduce this perturbation. However, they must be thick enough to withstand the 1-atm pressure difference. In Table 1, we compare several window materials. The thickness required is calculated from the simple hoop-stress formula, $\sigma = Pr / 2t$, using appropriate yield stress σ for each material. P is the pressure, r the radius of curvature of the window, which is assumed to be 1 mm, and t is its thickness. The equivalent gas thickness is calculated as the distance the initial window will expand to reach 10^{21} electrons / cm^3, based on the initial n_e shown in the second column of Table 1. This equivalent distance must be minimized. Based on these considerations, we chose polyimides as the window material, of which Kapton is a well-known commercial example. Polyimide is a family of plastic CH polymers used in integrated circuit fabrication. Although the chemical formula for the specific material used is proprietary, it is nominally $C_{22}H_{10}N_2O_4$ with a density of 1.4–1.5 g / cm^3.

The open-geometry targets need a nearly spherical volume of gas and must hold the pressure for 1–3 hr.

TABLE 1. Comparison of window materials.

Material	Electron density (moles/cm^3)	Thickness required	Equivalent gas thickness (µm)
Si_3N_4	1.72	0.2 µm	206
Lexan	0.74	0.8 µm	355
Kapton	0.72	0.3 µm	130
Parylene	0.56	0.8 µm	268

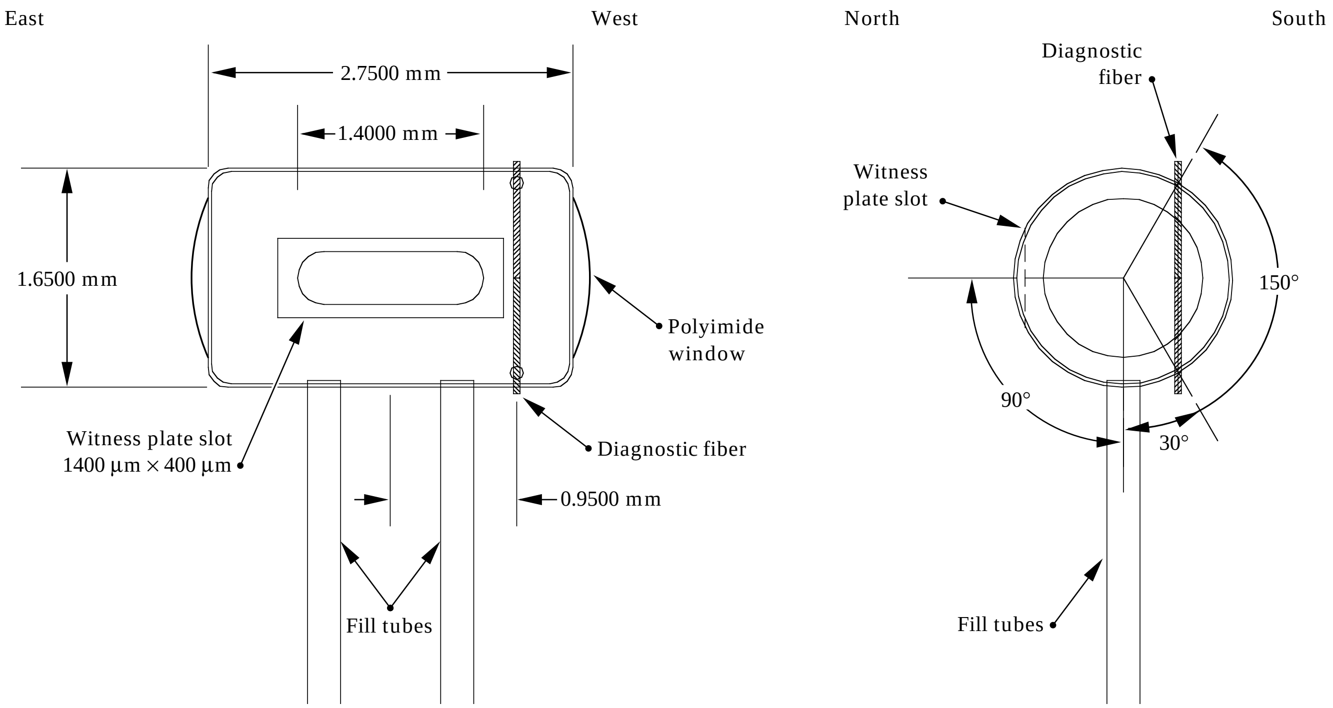

FIGURE 1. A CAD drawing of a closed-geometry target. (10-00-0795-1777pb02)

The target skin must endure >1 atm pressure over an area of ~20 mm^2, surrounded by a vacuum of $<10^{-5}$ Torr and be ductile enough to form a nearly spherical bubble from two flat sheets. The gas-bag targets are fabricated using brass, Lucite, and Al support washers (~400 µm wide). Fill tube holes (270 µm diam) are drilled through the side walls of the washers, which are microbead blasted to increase the surface area and to improve the polyimide / epoxy adhesion. A thin sheet of polyimide (~0.4 µm) is glued across both sides of a thin washer and two small-diameter stainless-steel fill tubes (~250 µm) are passed through the side wall into the inner diameter of the washer and glued in place. Pressurizing the fill lines (>20 psia) causes the films to distend, forming a nearly spherical bubble. Figure 2 is a photograph of a gas-bag target (with a 2.75-mm washer and a 2.4–2.5-mm-wide bag).

Nova's Au-hohlraum design serves as the model for the closed-geometry targets. Holes or slots are milled in the side of the target mandrel to view the target's interior (Fig. 3). Fill tube holes are also drilled into the side of the hohlraum mandrel to allow gas filling. After the Au-plated Cu mandrels are machined and inspected for accuracy, the outer surface is microbead blasted to produce a roughened finish. The mandrels are then leached in a nitric-acid solution ($HNO_3 \approx 0.5$ N solution) at 60˚C and etched (1–3 hr). The laser entrance holes (LEHs) and any diagnostic windows in the hohlraum are then covered with a thin (0.2–0.7-µm) sheet of polyimide.

The requirement to hold gas behind thin CH windows complicates target fabrication. The same basic assembly procedures used for non-gas targets are employed on the gas-cell target series. Target fabrication is generally performed using an optical microscope, with micromanipulators holding target parts in place with vacuum chucks and fast curing or UV / visible cured cements to affix target components.

For the open-geometry targets, the final assembly consists of mounting the target on a Nova magnetic target base at the desired orientation. Shields and imaging slits are attached to some of the open-geometry targets. The closed-geometry targets have additional alignment restrictions placed on them by alignment fibers and flags, backlighter patches, diagnostic holes, and slots. The target components are required to be placed within ±25 µm and ≤2°, relative to the Nova target base.

Gas Specification

The gas mixture and pressure are specified to mock up the experimental conditions for the point design of the NIF targets, using neopentane C_5H_{12} as the main gas in this series. To aid in measuring the ion temperature T_{ion} spectroscopic seed gases Ar and Freon–13 $CClF_3$ are added in concentrations from 0.25–10 at.%. The nominal standard target gas for the early experiments was 98% C_5H_{12} + 1% Ar + 1% $CClF_3$ at ~1-atm pressure. To achieve lower target densities, CO_2, C_3H_8, and CH_4 are used as the base gases. J. Colvin of Los Alamos National Laboratory (LANL) suggested obtaining a deuterated gas C_5D_{12} to potentially use the fusion neutron yield from the D as a diagnostic for the experiment.

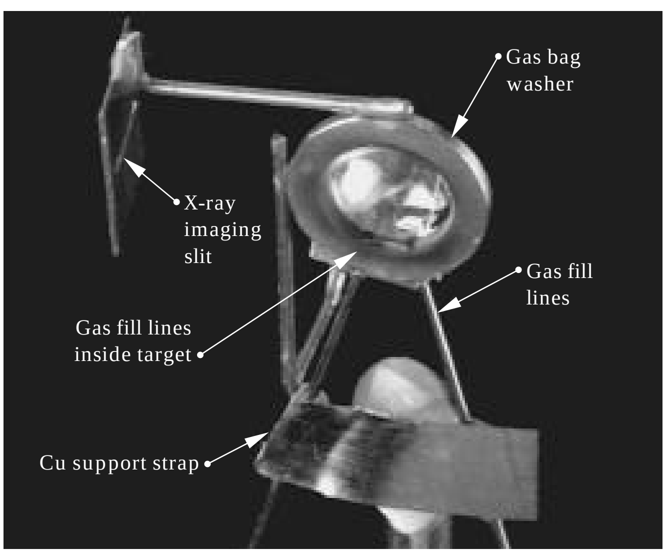

FIGURE 2. Photograph of a gas-bag target with an x-ray imaging slit. (10-00-0795-1778pb01)

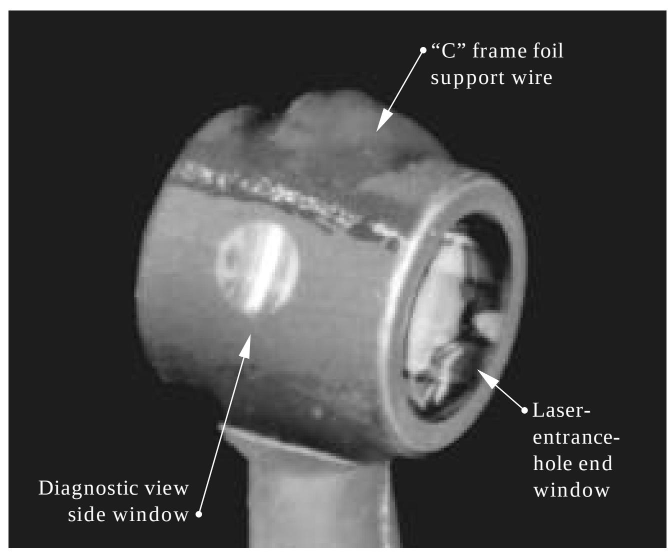

FIGURE 3. Photograph of a closed-geometry target showing the diagnostic view window. (10-00-0795-1780pb01)

A gas mixing manifold permits mixing of various gases into a sample bottle for later use in filling the targets (Fig. 4). As the main base gas C_5H_{12} condenses to a liquid at ~1300 Torr, an upper limit on the system is set at 1000 Torr. The gas mixture is specified in atomic percentage for the individual components. A diaphragm-style pressure manometer, insensitive to gas densities, monitors pressure in the gas mixing manifold and sample bottle. The sample bottle is connected to the manifold and the system is evacuated. The sample bottle valve is closed and the individual gases are purged three to four times to limit contamination of the final gas mixture. Exceptions to this purging process are C_5H_{12} and deuterated neopentane C_5D_{12}, due to their limited availability. The C_5H_{12} and C_5D_{12} bottles are directly connected to the main manifold with a small prechamber and a valve, which permits a small positive gas pressure to be maintained in the gas regulators and fill lines.

The gas with the lowest percentage in the mixture is first introduced into the manifold, and the pressure is allowed to increase until it reaches the desired partial pressure. The other gases are then added by partial pressure until the total pressure in the sample bottle reaches 1000 Torr.

To interpret the target results, it is necessary to know the ratios of the gases to <0.1 at.%. The gas mixtures are analyzed using a mass spectrometer with a resolution down to Z = 1 (H) and a discrimination down to 0.01 at.%. To improve the accuracy of the analysis, pure samples of each gas are drawn off into small (<75 cm^3) sample cylinders to be used as “reference” standards for all the starting gases and when primary gas source bottles are changed.

Target Manifold Design

A major restriction for the gas target fabrication is the limited space within the Nova target inserter (a cylindrical space 5 in. diam 16 in. long with the center 2 in. occupied by the target pylon); this space limitation drove our hardware choices. Figure 5 is a CAD drawing of a manifold fabricated out of brass to support the transducer, gas flow valves, and target fill lines. The valves were not designed for vacuum sealing but rather for liquid / gas flow metering, and after 6–10 shots, it is necessary to change the valves because they become one of the main sources of leaks on assembled targets.

A strain-gage-style, absolute-pressure transducer monitors manifold gas pressure. Prior to using this type of transducer, we field tested the unit to ensure its ability to operate not only at atmosphere on the bench but also in vacuum in the Nova target chamber. When the target is shot on Nova, a plasma is produced that has a designed T_e of 3 keV; to electrically protect the transducers, we added a Zener diode to each connector line on the transducer cable to strip off voltage spikes >50 V. The initial test transducer was calibrated before and after the first laser shot to check for any anomalies. The post-shot transducer voltage values were within ±0.001 V of the preshot values, verifying their robustness.

The early gas-cell targets used a flow-through method to fill the targets with gas, and two valves and gas lines were used on the manifold. One port on the target manifold was connected to the gas sample bottle. The gas flowed until it was estimated that all of the air in the target assembly had been displaced with the sample gas. The current system of evacuated backfill of targets retains the two valves to safeguard against one of the

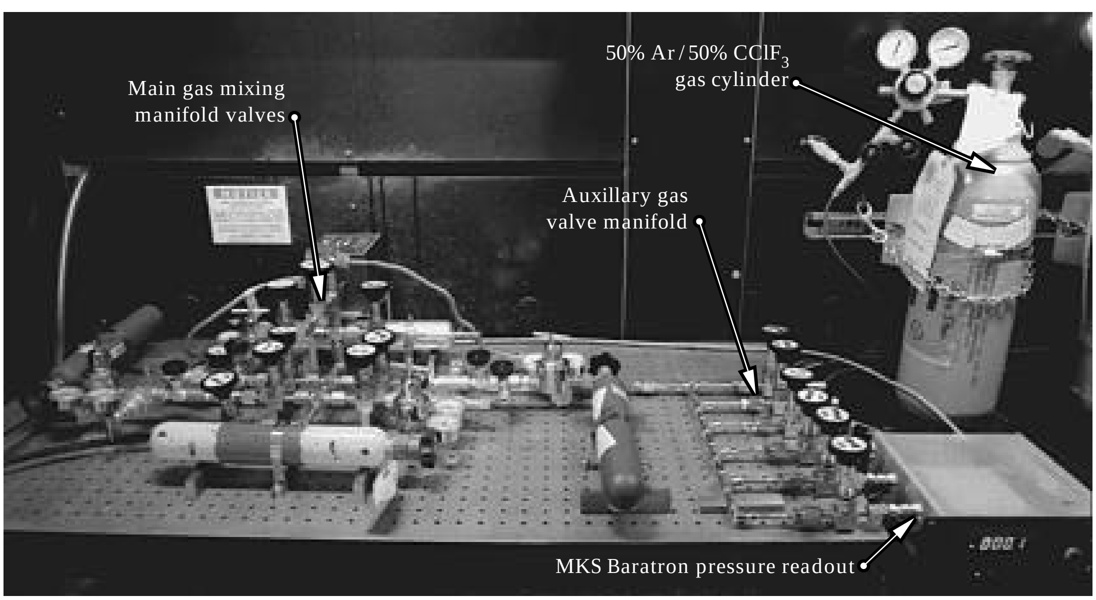

FIGURE 4. Photograph of a gas mixing system on an optical bread board table. (10-00-0795-1779pb01)

fill lines being blocked.[5] A pair of 1-mm-o.d. stainless-steel fill lines is attached to the top of the manifold. Plastic tubing is used to connect the manifold to the target. The target has stainless-steel fill lines (~250 µm o.d.) with smaller i.d. plastic tubing used to inter-connect the target to the plastic tubing on the manifold.

A separate pressure testing system, fabricated by LANL,[5] is used to test the target manifold. The test procedure is divided into three steps: (1) The target manifold is tested as a standalone unit. (2) The target body is tested and certified gas tight. (3) The assembled target attached to the manifold is tested as an integrated system before filling.

Target Filling Hardware and Procedures

The first targets were filled by flowing gas through the target, a method that used a large quantity of gas to ensure that only the sample gas remained inside the target. The new method, using an evacuation / backfill chamber, significantly reduces the total gas used per target.[5]

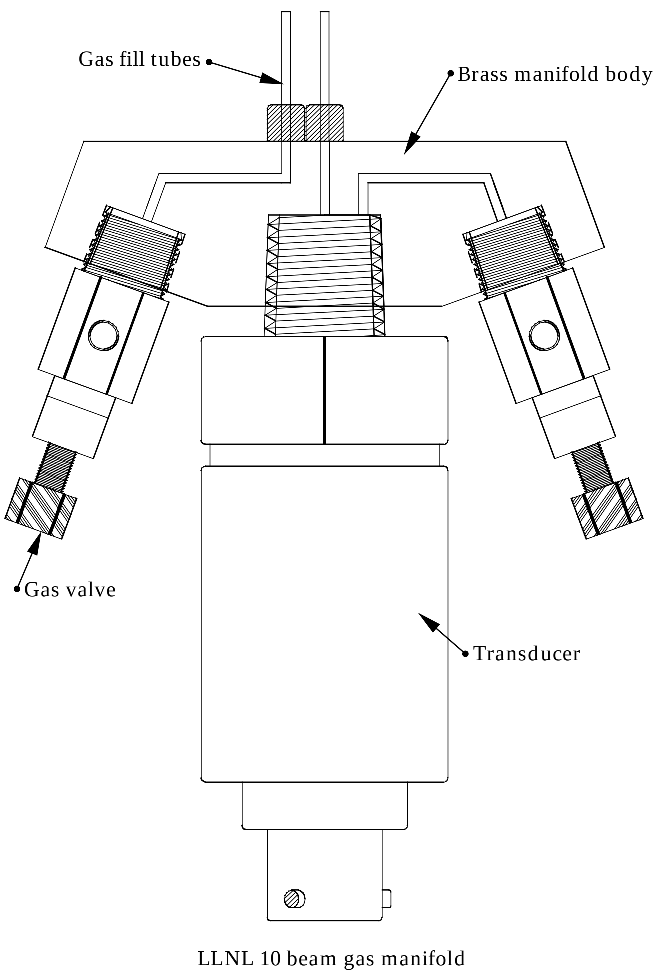

FIGURE 5. A CAD drawing of a target manifold with a transducer, valves, and gas fill lines. (10-00-0795-1781pb01)

The target filling manifold, with its calibrated pressure transducer attached, allows monitoring of internal target pressure at shot time. From this calibrated transducer, a pair of points for pressure vs voltage for vacuum and atmosphere are measured and the resulting values allow the final target pressure at shot time to be calculated. A mechanical manometer is also placed in-line with the fill chamber to monitor the external target pressure in the 1–200-Torr range. A small valving manifold is attached to the evacuation / backfill chamber to control the independent pumping of the target's interior and exterior and filling the target. Figure 6 is a photograph of this gas filling system.

The target and the gas fill line are connected to the target manifold. A purge line (~0.25–0.5 psig) is attached to the target manifold to verify that the fill lines are not blocked. The assembly is then placed in the evacuation / backfill chamber and the air around the target is slowly pumped out until the chamber pressure reaches ~5 mm Hg, then the interior of the target is slowly pumped out. Due to the low conductance of the fill tubes (100–250 µm), the pumping continues for ~15 min to fully remove the air from the target interior.

Once the base pressure inside the target is reached, the valves to the gas sample bottle are opened and the pressure inside the target is monitored. After the pressure inside the target has increased to the desired value, the chamber is slowly vented to atmosphere. The target manifold valves are closed and the transducer reading is observed for drift—if the target pressure is stable, the fill line is disconnected and the target is ready for delivery to Nova.

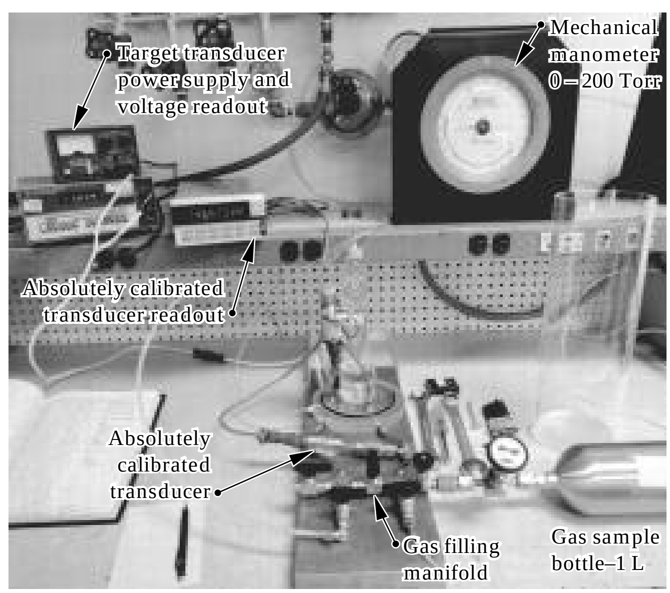

FIGURE 6. Photograph of the evacuation / backfill chamber and gas filling system. (10-00-0795-1816pb02)

Summary

Targets to test the point design for the proposed NIF were developed and fabricated for use on the Nova laser at LLNL. Sub-micrometer-thick polyimide windows capable of holding >1 atm were attached to closed-geometry (Nova-hohlraum-style) and open-geometry (nearly spherical gas-bag) targets. Together with the Target Fabrication group at LANL, we fabricated a system to pressure-test targets and to verify gas integrity, prior to delivery to Nova. We also developed a gas-mixing system that permits mixture ratios as low as 0.25 at.% for individual gases and a system to measure gas pressure inside the target to integrate into the Nova target positioner. In support of the ICF programs at LANL and LLNL, more than 450 gas-cell targets have been successfully fielded on Nova.

Notes and References

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2. J. Lindl, "Development of the Indirect-Drive Approach to Inertial Confinement Fusion and the Target Physics Basis for Ignition and Gain," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-119015 (1995).
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4. B. J. MacGowan, C. A. Back, R. L. Berger, et al, "The Study of Parametric Instabilities in NIF-Scale Plasmas on Nova," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-118524 (1995); prepared for the Proceedings of the International Atomic Energy Agency *15th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, Seville, Spain, Sept. 26–Oct. 1, 1995.
5. M. Salazar and the LANL Target Fabrication group are responsible for the original design and fabrication of the evacuation test chamber system and the evacuation backfill method. Their staff is also responsible for fabricating the additional gas handling hardware used for target testing.